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Published in:
Monthly Notices of the Royal Astronomical Society Letters

DOI:
10.1093/mnrasl/slt066

Publication date:
2013

Citation for published version (APA):
Morgan, H. (2013). An observation of solar active region expansion into the heliosphere. *Monthly Notices of the Royal Astronomical Society Letters*, *433*(1), L74-L78. https://doi.org/10.1093/mnrasl/slt066

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRASL 433, L74–L78 (2013)
Advance Access publication 2013 June 10
doi:10.1093/mnrasl/slt066

An observation of solar active region expansion into the heliosphere

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Accepted 2013 May 15. Received 2013 May 13; in original form 2013 April 30

ABSTRACT

According to current models, solar closed-field active regions are isolated from contributing directly to the solar wind except through small- or large-scale magnetic reconnection, including coronal mass ejections. Here we show the first direct evidence of active regions contributing directly to the solar wind by a steady-state, quiescent expansion. Advanced image processing of coronagraph data reveals a large system of nested closed-field magnetic structures expanding and accelerating to heights of at least 14 $R_\odot$ within a helmet streamer above a large active region. The system persists for several days, and must therefore be an important contribution to the slow solar wind.

Key words: Sun: corona – Sun: heliosphere – Sun: magnetic topology – solar wind.

1 INTRODUCTION

Active regions are areas of the low corona associated with the emergence of closed magnetic flux through the photosphere. Their high density and temperature lead to enhanced emission in X-ray and extreme ultraviolet (EUV) emission lines of highly ionized species. The expansion of active regions in the low corona was first observed in soft X-ray observations two decades ago (Uchida et al. 1992). The observations were limited to heights $<0.5\,R_\odot$ above the solar limb due to the intrinsic sharp drop in X-ray signal with height and the field-of-view (FOV) limit of the instrument. Despite this limitation, the observations were interpreted as if the expansion continued into the extended corona and solar wind. Connected to this discovery, some in situ studies of the heliospheric solar wind have mapped some slow wind flows directly to active regions at the Sun (Kojima et al. 2000; Neugebauer et al. 2002), and certain solar wind signatures have been discussed in the context of active region closed field (Gopalswamy et al. 2013). There are many studies of plasma outflows from open-field regions within, or bounding, active region complexes (for an overview, see the detailed introduction of Slemzin et al. 2012). Both Slemzin et al. (2012) and Harra et al. (2008) find steady outflows with velocity of the order of a few tens of km s^{-1} at the edges of active regions, interpreted as sources of slow solar wind. Wang, Ko & Grappin (2009) show, using in situ measurements and models of the low corona, that slow wind flows with typical ion compositions arise from small coronal holes near active regions. Kojima et al. (1999) reached similar conclusions using radio observations of the solar minimum corona. These outflows are all assumed to flow along open-field regions in the vicinity of active regions, and many studies invoke magnetic reconnection as a mechanism to release active-region-type plasma into the solar wind. There is no doubt that a large component of the slow wind arises from regions bounding active regions. However, the direct quiescent expansion of the closed-field active region itself is not generally included in current models, and interpretations of solar wind measurements in terms of direct links to active regions are rare due to the lack of observational evidence of active region expansion in the extended corona. In current models, the active region solar wind contribution is limited to small-scale magnetic reconnection with neighbouring open-field regions or larger eruptive events.

New image processing techniques applied to coronagraph images reveal a plethora of previously undetected faint dynamic events (Morgan, Byrne & Habbal 2012). The processing removes the signal from slowly changing quiescent structures, thus greatly amplifying the relative signal from faint dynamic structures. One important discovery resulting from the new technique is the expansion of closed loops above active regions, which is found to be a common phenomenon. An example possessing typical characteristics is described here.

2 METHOD SUMMARY

The Large Angle and Spectroscopic Coronagraphs (LASCO) (Brueckner et al. 1995) aboard *Solar and Heliospheric Observatory* (*SOHO*) have observed the corona in visible light for almost 17 years. In early 2011, the observational cadence of the C2 coronagraph was on average around 12 min with only occasional data gaps of longer than a few hours. After removing long-term minimum backgrounds from the images, the normalizing-radial-graded filter (Morgan, Habbal & Woo 2006), which removes the steep radial drop in brightness, is applied. The resulting images contain slowly changing quiescent coronal structures (i.e. streamers and coronal holes), which are close to radial in structure, plus dynamic

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events which are generally non-radial, and, by definition, changing rapidly compared to the quiescent structures. The quiescent and dynamic components are separated by applying deconvolution along the radial and time dimensions of a data cube, which gives a set of images which contain only noise and dynamic coronal events, with the quiescent structure removed. The method is superior to the more commonly used running difference images for several reasons. The quiescent–dynamic separation by deconvolution removes most of the quiescent structure by exploiting the smoothness of the quiescent structure in the radial direction; thus, noise is not inherently amplified. Currently, no other method can reveal such faint detail of the dynamic corona with such clarity. See Morgan et al. (2012) for full details of the method.

3 OBSERVATIONS AND RESULTS

Early 2011 is a period of rising solar activity with plenty of large active regions yet low coronal mass ejection (CME) activity compared to periods of maximum activity. This allows for long quiet periods which are ideal for the study of fainter dynamic structures. The dominant feature of the south-west corona at the beginning of 2011 March is a large and bright (high-density) helmet streamer, one leg of which sits above a large active region (Fig. 1). From an analysis of potential field source surface (PFSS) coronal magnetic extrapolation maps, this streamer is associated with the heliospheric current sheet (HCS). This is a surface in the extended corona and heliosphere where the magnetic field changes sign, associated with the highest density slow solar wind. The standard model of such a streamer would be a closed-field region at the base, with the open field from the streamer boundaries bridging over the closed field to meet at the cusp, at a height of $\sim 1\,R_\odot$ above the limb. The open field above the cusp forms the HCS, appearing as a bright streamer stalk in coronagraph images which extends radially out to the heliosphere.

An active region situated at the northernmost base of the streamer is just the south of the equator. It is very large, and EUV observations reveal a plethora of small-scale events in the active region core including loop brightenings, some small ejections, emerging flux and rapid expansion of loops. Some of this large-scale expansion is shown in Fig. 2, using observations by the Atmospheric Imaging

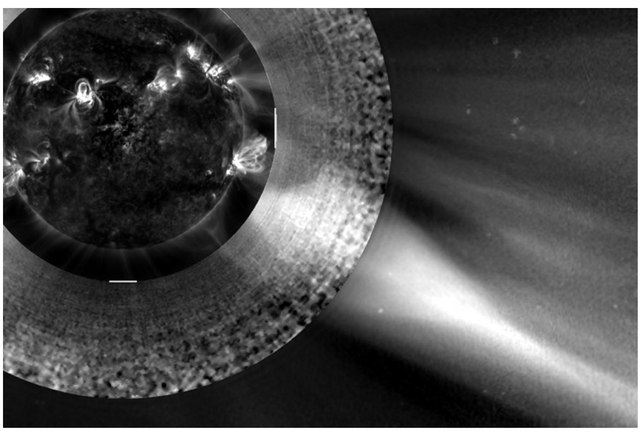

Figure 1. The south-west corona during 2011/03/07. This region is dominated by the large bright helmet streamer sitting above an active region which is a little south of the west equator. The inner corona is an EUV observation dominated by emission from Fe 9+ (temperature of formation $\sim$1 MK), and the extended corona is coronagraph observations of Thomson-scattered light from free coronal electrons.

Assembly (AIA) onboard the *Solar Dynamics Observatory* (*SDO*) spacecraft. This expansion is a continuous process apparent over several days, with new systems of smaller loops appearing in the active region core and expanding to large heights beyond the FOV of the instrument. This behaviour is typical of many variable active regions. The rapid evolution and intense brightenings in the active region core are indications of emerging flux, and this activity is driving the expansion of the active region far beyond its normal spatial extent. The expansion speed of the loops as measured in the EUV observations at heights below $0.5\,R_\odot$ is approximately $10\,\mathrm{km\,s^{-1}}$, in agreement with a previous study (Uchida et al. 1992).

The LASCO (Brueckner et al. 1995) instrument is a suite of space-based occulted telescopes aboard the *SOHO*, which orbits the L1 Lagrangian point between Earth and the Sun. Processed LASCO C2 (FOV = 2.2–6.0 $R_\odot$) observations of the streamer above this active region reveal a nested system of expanding loops within the streamer, as shown in Fig. 3. The expanding loops are clearly outlining an expanding closed-field system contained within the large helmet streamer. The loops are huge, with a latitudinal extent of a few tens of degrees. They remain structurally coherent throughout the LASCO C2 FOV. The coronagraph signal-to-noise ratio drops rapidly with increasing height. Nevertheless, with large image contrast enhancement we can view the expanding loops to at least $14\,R_\odot$ above the limb in LASCO C3 observations, as shown in Fig. 4.

The loops first become apparent at approximately 2011/03/07 00:00 and persist for 44 h until a large eruption from the active region disrupts the system. Fig. 5 shows a height–time plot of brightness along a radial line at the centre of the streamer. The expanding loops appear as enhancements along the height–time plot and show a non-linear profile indicative of acceleration. The speed of the loops is approximately $20\,\mathrm{km\,s^{-1}}$ at $\sim 1\,R_\odot$ above the limb, accelerating linearly to $60\,\mathrm{km\,s^{-1}}$ at $4\,R_\odot$ above the limb. This is consistent with the $\sim 10\,\mathrm{km\,s^{-1}}$ expansion speed and acceleration of the active region as observed in EUV at heights $<0.5\,R_\odot$. Loops appear fairly regularly with a frequency of one per 3 h. These characteristics seem typical of expanding active regions.

4 DISCUSSION

The exact mechanism driving the expansion is unknown. The active region is highly variable, and from viewing AIA movies of the region, there seems to be considerable flux emergence. The relatively high plasma pressure in the active region, and the emerging magnetic flux, may help drive the expansion. Rather than leading to a catastrophic eruption, or the smaller scale plasmoid ejections of the 'leaky faucet' model (Fisk 2003; Sheeley, Warren & Wang 2007), a simple quiescent expansion of the closed field into the extended corona can occur. In this case, the underlying closed field must be replenished by new flux emergence through the photosphere, or at least an expansion of a pre-existing system of smaller loops. It is known that the base of streamers can experience a period of expansion, followed by a rapid event which results in the ejection of a plasmoid and a contraction of the streamer base ('in-out pairs') (Sheeley & Wang 2007). A parameter study of this phenomenon for a model streamer (a simple dipole and current sheet) showed that the expansion and subsequent reconnection were sensitive to the rate of magnetic field replenishment at the base of the system (Sheeley et al. 2007). Indeed, given sufficient replenishment of closed field at the base, the system could expand to the heliosphere without reconnection and subsequent contraction. Despite the simplicity of this process, and its underlying importance for the theory

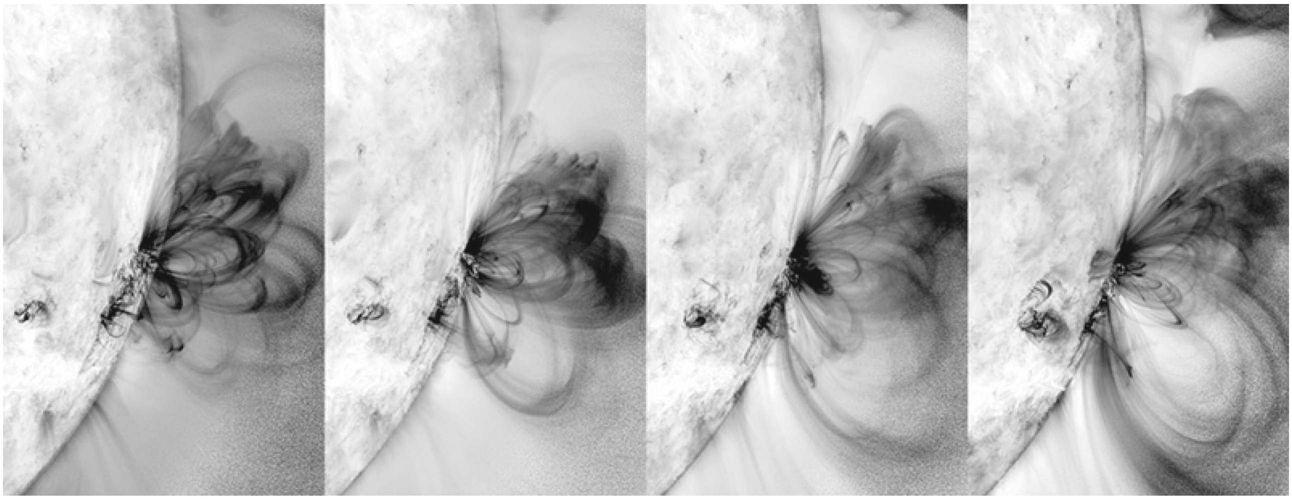

Figure 2. Details of the active region as observed in EUV on 2011 March 8 for times 01:20, 05:30, 11:40 and 18:10 (left to right). For clarity, the brightness values are inverted so that bright features are darkest.

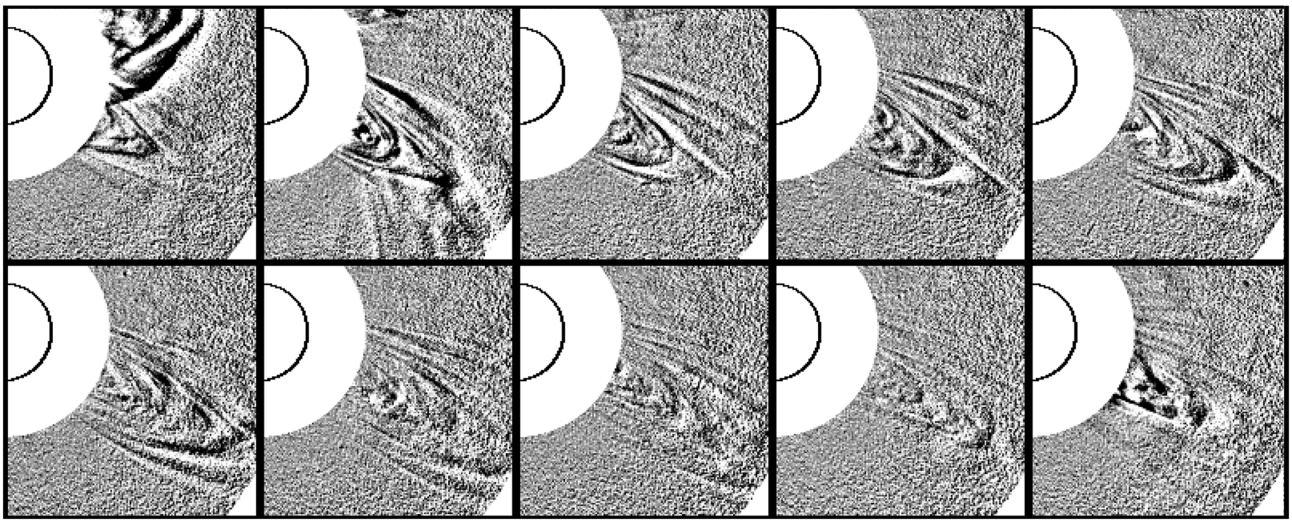

Figure 3. Time sequence of LASCO C2 observations of the south-west corona processed to reveal faint dynamic events. In these images, the slowly changing brightness of the large streamer is removed, revealing a set of large expanding loops (and other dynamic phenomena). This sequence begins on 2011 March 7 (20:08) and lasts nearly 24 h. For clarity, the brightness values are inverted. The expanding loops are therefore dark in these images.

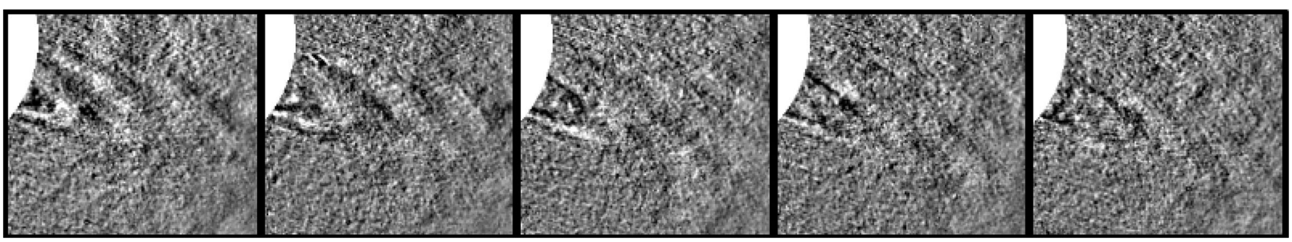

Figure 4. Expanding loops seen at large heights in LASCO C3 observations. The signal of the loops at these heights is barely above the noise level. Nevertheless, the distinct nested loop structure is apparent. Brightness values are inverted.

of solar wind formation, it is excluded from current models due to a lack of observational evidence. Therefore, the discovery presented here necessitates considerable revision of models describing the connections between the Sun and the heliosphere. In particular, large-scale global magnetohydrodynamic models (e.g. Linker et al. 1999) which aim to simulate the coronal and heliospheric environments will need to include the emerging flux in active regions, with an aim to replicate the expansion of active regions into the heliosphere. This discovery also has implications for the accuracy of PFSS modelling. PFSS is used to extrapolate the observed photospheric magnetic field into the corona, and is the main method for estimating the topology of the corona and heliosphere – in particular the position of the HCS (Altschuler & Newkirk 1969). The expanding loops are propagating along the HCS, and their broad latitudinal extent implies an unexpected nature to the region of the neutral sheet which contains the loops.

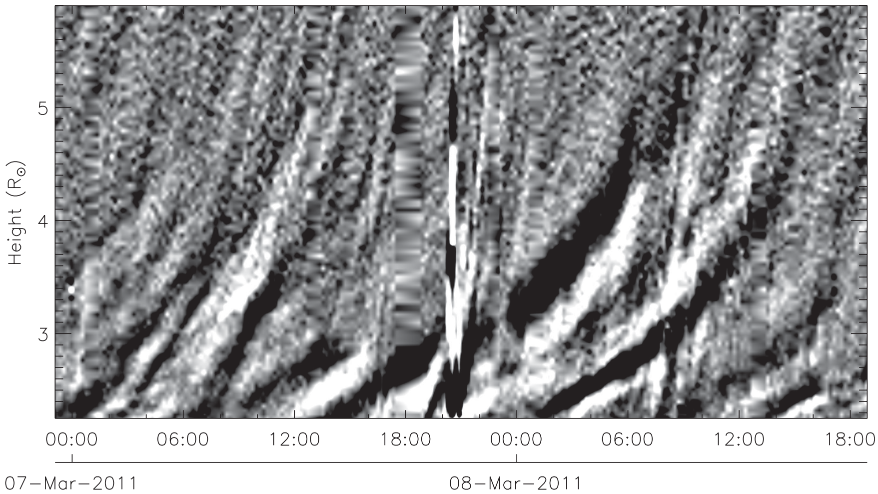

Figure 5. Height–time plot showing brightness within the streamer for a 38 h period. A radial line is traced in the coronagraph images at the centre of the streamer, and these radial brightness profiles are stacked in time. Any bright feature moving outwards will describe a bright curve in the height–time plot. The expanding loops appear as lines of enhanced brightness and are curved due to acceleration with increasing height. The black regions are of low brightness, situated in between the expanding loops.

The slow solar wind is highly variable in speed, density and composition. There is not yet a single model at present that describes its origins and explains all its observable characteristics in a unified manner (Antiochos et al. 2012). That expanding active region closed-field loops remain structurally coherent to large heights, and are continuing to expand without narrowing or dispersing, suggests that they persist as closed-field regions into interplanetary space. This provides a direct path for active region plasma to contribute to the solar wind, without magnetic reconnection or large-scale eruptions. This provides a fresh explanation to certain characteristics of the slow wind. Active regions, particularly very active ones, contain localized regions of high-temperature plasma which drives ions to high charge states (Aschwanden et al. 2013). Current models underestimate the ionic charge states of the slow wind, and solutions to this inaccuracy involve the unsteady release of slow wind out of a heated structure (Fisk 2003). Mechanisms for this release are based on reconnection between hot closed field (active regions) and the open field of the solar wind (Antiochos et al. 2012). The expansion of closed-field loops provides an alternative source of high-charge-state plasma directly into the slow solar wind. As these regions expand into the extended corona, the density drops to a collisonless regime; therefore, the charge states become frozen in and carry a record of active region conditions into interplanetary space (Ko et al. 1997; Habbal et al. 2010).

Expanding loops provide a partial explanation for the highly variable nature of the slow solar wind. Coronal helmet streamers, as the one shown here (Fig. 1), have an extended structure along the line of sight, whilst the expanding loops are probably narrow structures, with limited extent along the line of sight. Therefore, even though the brightness of the expanding loops is only around 3 per cent of the background streamers, their relative density must be considerably higher. These slow and dense closed-field features will likely carry a signature out to the heliosphere as density variations to the background, continuous slow wind. They are likely to introduce variability in the bulk outflow speed, charge states and composition, and magnetic field orientation and strength. These are all factors which should be addressed in future studies. In particular, a simple model of how typical active region loop plasma characteristics evolve as they expand into the collisonless regime of the extended corona will be essential to make meaningful comparisons with in situ measurements.

Counterstreaming electrons (CSEs) are suprathermal electron populations in the solar wind which flow parallel and antiparallel to the magnetic field (Gosling et al. 1987). One proposed mechanism for CSEs is closed-field magnetic fields with footpoints at the Sun, generally believed to exist exclusively within interplanetary CMEs. Indeed, a large statistical study of CSEs has been made during a period of low CME activity in order to better establish the relative contribution of CMEs as a proposed source mechanism (Lavraud et al. 2010). As active region closed loops are quietly expanding as part of the solar wind, active region suprathermal electrons have a direct path to the heliosphere in the absence of CMEs, providing an alternative explanation for CSEs in the solar wind.

In summary, the direct expansion of active regions into the heliosphere is a new discovery which presents a new challenge for current models of the connection between the Sun and heliosphere, and may present solutions for current unexplained characteristics of the heliospheric solar wind. It also has important implications for the dissipation of newly emerged magnetic flux at the photosphere and the replenishment of the heliospheric magnetic field by the Sun.

ACKNOWLEDGEMENTS

The author wishes to thank the anonymous referee whose comments improved this Letter greatly. The author is grateful for funding from the Coleg Cymraeg Cenedlaethol to Prifysgol Aberystwyth and support of SHINE grant 0962716 and NASA grant NNX08AJ07G to the Institute for Astronomy, University of Hawaii. The SOHO/LASCO data used here are produced by a consortium of the Naval Research Laboratory (USA), Max-Planck-Institut fuer Aeronomie (Germany), Laboratoire d'Astronomie (France) and the University of Birmingham (UK). SOHO is a project of international cooperation between ESA and NASA.

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